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MULPEX: a compact multi-layered polymer foil collector for Micrometeoroids and Orbital Debris.

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Abstract

Detailed studies of preserved hypervelocity impact residues on spacecraft multi-layer insulation foils have yielded important information about the flux of small particles from different sources in low-Earth orbit. We have extended our earlier research on impacts occurring in LEO to design and testing of a compact capture device. MULPEX (**MU**lti-**L**ayer **P**olymer **EX**periment) is simple, cheap to build, lightweight, of no power demand, easy to deploy, and optimised for the efficient collection of impact residue for analysis on return to Earth. The capture medium is a stack of very thin (8 micron and 40 micron) polyimide foils, supported on poly-tetrafluoroethylene sheet frames, surrounded by a protective aluminium casing. The uppermost foil has a very thin metallic coating for thermal protection and resistance to atomic oxygen and ultra-violet exposure. The casing provides a simple detachable interface for deployment on the spacecraft, facing into the desired direction for particle collection. On return to the laboratory, the stacked foils are separated for examination in a variable pressure scanning electron microscope, without need for surface coating. Analysis of impact residue is performed using energy dispersive X-ray spectrometers. Our laboratory experiments, utilising buck-shot firings of analogues to micrometeoroids (35-38 micron olivine) and space debris (4 micron alumina and 1mm stainless steel) in a light gas gun, have shown that impact residue is abundant within the foil layers, and preserves a record of the impacting particle, whether of micrometer or millimetre dimensions. Penetrations of the top foil are easily recognised, and act as a proxy for dimensions of the penetrating particle. Impact may cause disruption and melting, but some residue retains sufficient crystallographic structure to show clear Raman lines, diagnostic of the original mineral.

1. Introduction

The longevity and high performance of spacecraft systems depend partly upon mitigation of hazards in the space environment. Hypervelocity collision with natural micrometeoroid (MM) or artificial space debris (SD) may cause a wide range of effects from physical penetration through vulnerable surfaces, generation and propagation of high velocity spall fragments, and creation of high temperature electrically conductive plasma. In at least two documented cases, the teams analysing operational spacecraft anomalies have concluded that hypervelocity impact was responsible for damage: the microsatellite Cerise, struck by a substantial discarded launcher component (Alby et al., 1997); and the Olympus telecommunications satellite, probably struck by a small cometary particle associated with the Perseid meteors (Caswell et al., 1995). Much effort has gone into the design of robust external shielding (Committee on International Space Station Meteoroid/Debris Risk Management, 1997), and the implementation of safe-attitude postures during times of perceived threat such as the Leonid stream maxima (Ailor et al., 1998).

In order to assess the necessary level of physical barrier required for a particular satellite, and mindful of the need to balance the desirability of precautionary shielding against the cost of extra mass for launch to orbit, it has proven useful to employ predictive models of particle flux (e.g. Sdunnus et al., 2001 and Liou et al., 2001). These numerical simulations of particle numbers require calibration and testing (McDonnell et al., 2001a), which in turn has required measurement of the number and size of impact features on returned spacecraft surfaces. Large areas of space-exposed structures (such as solar arrays) have proven to be valuable passive collectors of particle remnants. The size of impact features can be related to original particle properties by experimental calibration in hypervelocity gun shots (Drolshagen et al, 1997, Taylor et al., 1999) and by complex numerical simulations (McDonnell et al., 2001b). For 'semi-infinite' thickness ductile targets (e.g. metal plates), the crater form is sensitive to a wide range of factors including particle velocity, incidence angle, mass, density, shape, hardness and crystallographic structure (e.g. Wallis et al., 2002). It is therefore helpful to be able to determine as many of the impacting particle characteristics as is possible from the impact feature. Chemical analysis of projectile residues within spacecraft impact features has provided clues as to the MM mineralogy or SD composition (Graham et al., 2001). From these data it is then possible to estimate density and hardness characteristics and to partially predict particle behaviour during the impact process.

2. Surveys of micrometeoroid and space debris particle flux

2.1 Demands of a survey

The primary objective of a survey is reliable determination of the number of impacts by particles of specified sizes, of all compositions, on a standard area, in a unit of time, at a particular altitude. Fluxes are often reported as logarithmic scale graphs of the cumulative number of features plotted against diameter of the impact feature. It is therefore necessary to be able to accurately measure each feature, and helpful to be able to cross correlate to other datasets that may be based upon features developed upon different impact substrates. An ultimate goal is to determine the likely size/mass of each particle, which requires an assessment of impact velocity by reference to the particle origin, based upon analysis of the residue composition. Although basic classification into space debris and micrometeoroids may suffice for flux modelling by revealing the broad velocity regime, it is also very helpful to know as much as possible concerning the composition of the impactor, especially for further interpretation of micrometeoroid origin.

2.2 Historical basis and the current status of surveys

As well as evaluation of the response of specific materials when exposed to the low Earth orbit (LEO) environment, there have been several extensive surveys of impacting particle flux including: impacts on aluminium metal clamps on the Long Duration Exposure Facility (LDEF, Bernhard et al., 1993); on solar cells from the European Retrievable Carrier (EuReCa, Drolshagen et al., 1996) the Solar Max satellite (Kessler et al., 1985; Warren et al., 1989) and Hubble Space Telescopes (HST, Graham et al, 2001a); and on multilayer insulation foils from the Space Flyer Unit (SFU, Yano et al., 1997; Kearsley et al., 2002) and the Mir Trek Cosmic Ray Experiment (Graham et al., 2003). In each case an opportunistic selection of a space-exposed surface has yielded important, but incomplete, flux data. Recent use of silica aerogel collectors has also permitted detailed documentation of lesser particle numbers (Hörz et al., 2000). All of these studies have relied upon sample storage within Soyuz capsules, or the ability of shuttle orbiter missions to rendezvous with spacecraft, retrieve components and return relatively bulky samples from orbit. With the restriction of mission potential following the loss of Columbia, and competing demand from construction of the International Space Station (ISS), stowage space is at an even greater premium. Further surveys of damage are likely to be restricted to external examination of the ISS and the deployment of relatively small devices, probably active sensors, unless lightweight large-area collectors can be produced. There is currently no prospect for return of exposed material from geostationary orbit for post-flight investigation.

2.3 Limitations of existing collection substrates and analytical methods

A thorough discussion of the possibilities and problems associated with survey of impact residues on different types of substrate was given by Graham et al (2001b). It was demonstrated that whilst the large surface area sampled during surveys of returned solar cells allows recognition of large numbers of impacts, the composition of the cell prevents easy recognition of silicon-bearing debris or non-mafic silicate micrometeoroid minerals. Thus silicone-based paint binders (e.g. poly-methoxysilicone), silicate glass (e.g. borosilicate solar cell cover glass) and meteoritic feldspar (e.g. Ca and Al-rich anorthite) or chondrule mesostasis glass (Na-, Al- and Ca-rich) are very difficult to distinguish upon solar cells. Light gas gun shots of coarse (40 micron) feldspar particles can leave recognisable Ca- and Al-rich residue on solar cells, but only two Al- and Si- rich residues were found in our extensive survey of HST impacts from LEO (>150 impact features analysed). Whether this is truly due to confusion with the glass substrate or reflects a paucity of such compositions in the Earth-crossing micrometeoroid population is unknown. Crystalline Ca- and Al-rich silicates (feldspars) are known to be abundant in ordinary chondrite meteorites, which dominate both fall and find collections of meteorites, and which are believed to be representative of particles of S-type asteroid origin (Binzel et al., 2004). Potential for recognition of their residue is therefore an important matter in the determination of whether particles are derived from specific asteroidal or cometary origins, and therefore the most appropriate velocity model to use (20 kms-1 or 70 kms-1, yielding almost an order of magnitude difference in kinetic energy per unit of mass). Fortunately, magnesium and iron-bearing silicates can usually be recognised from the characteristic enrichment of these two elements within melt of the homogeneous solar cell cover glass.

In contrast, Si-rich residue is relatively easy to find on commercial multi-layered insulation (MLI) made from aluminised Kapton foils (thin metallic aluminium on polyimide foil), as there is no confusion with background composition. However, aluminium-bearing debris, whether metal or oxide, is very difficult to distinguish on MLI as it appears very similar to the aluminium particles created by delamination of the reflective metallic layer during the impact process. Ironically, studies of impacts on MLI (Kearsley and Graham, 2004, Graham et al., 2004) involving dissection of the individual foil layers has revealed that they are very efficient collector of residue from the impacting body. MLI thus has one important collector characteristic, but fails upon another criterion.

Metal foils of more than a few microns thickness, such as those employed in several previous surveys, may rapidly reveal impact perforations, but even the limited metal thickness results in extensive particle damage, and the substrate itself may present substantial analysis problems. Gold generates a complex suite of M-series X-ray lines of energies at around 2 keV, very similar to those of sulphur and phosphorus, both important micrometeoroid marker elements. As determination of the impact residue chemical composition is likely to be the rate limiting step in most investigations it is important to use analysis protocols that yield data quickly. Energy dispersive X-ray microanalysis has proven effective in this role, yielding compositional data from the area of an impact feature within a few seconds (Graham et al., 2001b). Unfortunately, EDS has relatively poor X-ray energy resolution, making the overlap of the Au, P and S emission lines difficult to resolve, especially when Au is dominant. Although wavelength dispersive X-ray microanalysis provides a very low detection limit and can readily separate the signal from Au, P and S (as well as other similar peak overlaps), it does require a smooth substrate and is relatively slow. It is therefore inappropriate for rapid residue determination in a large survey. Fortunately, there are few problematic emission line overlaps to be resolved in the analysis of most micrometeoroid and space debris materials, precise quantification of minor and trace elements is rarely a substantial issue, and EDS is therefore adequate for residue classification. It has the added advantage that it need not compromise the subsequent use of other analysis techniques such as secondary ion mass spectrometry (SIMS), itself a destructive technique. The advent of modern low vacuum/variable pressure scanning electron microscopes such as the Jeol 5900LV and LEO 1455VP in use at the Natural History Museum, has also obviated the need for conductive coating of the sample surface, thereby removing another possible source of surface contamination, and shortening preparation time.

Numerous studies of laboratory- and space-exposed silica aerogel have shown that it can be a remarkably successful capture medium for fast moving particles, although delicate structures may be disrupted within the impact feature (Graham et al., 2004). Even with the advances described by Westphal et al (2004), sample handling and preparation are relatively slow up to the point of particle microanalysis (minutes to hours per feature), and some of the more powerful 'remote' analysis techniques require expensive instrumentation (e.g. proton induced X-ray emission, Graham et al., 2004) or only yield useful information from a restricted suite of materials e.g. Raman spectroscopy is good for mineral characterisation (Burchell et al., 2004), but yields no information about space debris metals. Due to the fragile nature of aerogel it requires careful handling and carriage with a specially designed containment which may be of relatively high mass if a large surface area of aerogel is to be exposed. These characteristics may be less important in a mission such as Stardust (Brownlee et al., 1997) where cometary sample collection may occur at rates of hundreds of particles per second (Tuzzolino et al., 2004). However, for typical cumulative fluxes of 10^{-5} $m^{-2}s^{-1}$ as seen in damage surveys of the Hubble Space Telescope (McDonnell, 1998), where debris and micrometeoroid distinction is the main objective, rather than sophisticated geochemistry, this presents a rather inefficient ratio of impact residues per unit mass. The lengthy extraction techniques for samples in aerogel also preclude rapid analysis and interpretation.

That it is necessary to examine large areas for a statistically significant sample of impacting particles is clearly demonstrated by the disparity between neighbouring solar cells returned from HST service mission 3B. Counts of impact features on cells separated by no more than 10cm showed that one cell might show as few as seven impacts, and another as many as nineteen. Analysis of residue contents and the particle direction of flight also demonstrated that the cells with large numbers of impacts contained a wide variety of residue compositions, from particles travelling in a wide range of directions, evidence to suggest that they were not the result of a 'swarm' of particles such as those described from Mir aerogel samples by Hörz et al. (2000). Modern measurements of particle flux in LEO (McDonnell, 1998) demonstrate that approximately 2,500 impacts that create features of more than 5 micrometres diameter on solar cell glass might be expected to occur per square metre per year, but with relatively few of the larger (millimetre-scale) impactors that are of particular interest in a damage survey.

3 Characteristics of an ideal collector

There is thus a need for a collector design that would allow rapid post-flight analysis of large numbers of residues from particles over a range of four orders of magnitude in size, of the widest possible compositional range. The collector should also provide a simple and reliable proxy of particle dimensions, it should be cheap to build, lightweight for launch and return, simple in design to make easy for deployment and retrieval, and easy to disassemble for post-flight analysis. The collector substrate should be of a composition that does not interfere with analysis of any of the particle compositions, yet must be able to withstand the LEO environment for intervals of months to years. It should allow capture of a large proportion of the impacting particle and should subject the material to the lowest possible shock state. The substrate must also be suitable for rapid examination and analysis, with a minimum of preparation and preferably by automated image and compositional analysis routines. During launch and retrieval the collector should be able to stow into a small volume, in larger versions unrolling or unfolding to present a large surface area when installed on the spacecraft exterior. All of these criteria can be met by our MUlti Layer Polymer foil EXperiment (MULPEX).

4. Construction materials for MULPEX variants

Our experience of impact feature and residue location and analysis on MLI from SFU and Mir Trek (Graham et al, 2003, Kearsley and Graham, 2004) led to consideration of Kapton foils as raw materials for construction of a dedicated collector, in which the normal functions of the blanket could be set aside to optimise impact residue analysis. Our first two laboratory test devices had polyimide foil layers that were supported upon, and spaced by, polystyrene sheet frames of 2 mm thickness (figure 1).

Poly-tetrafluoroethylene (PTFE) sheet is proposed for the support frames of the first collectors intended for space exposure as the durability of this material is well proven, demonstrated in repeated successful use of 'betacloth', which has a PTFE surface layer. The uppermost foil layer of MULPEX, which is directly exposed to the harsh LEO environment has the most exacting physical requirements, in that it should be sufficiently protected and thick enough to survive for a period of months to a few years in orbit, whilst thin enough to permit full penetration by particles of micrometer scale. The thick (80 micron) singly aluminised Kapton of normal MLI, which is exposed in LEO as a surface of clean golden-coloured polyimide has shown that it is sufficiently corrosion resistant to survive for at least a year. Unfortunately the great excess of foil thickness to the size of typical space debris particles (1 micron) would probably result in destruction of finer particles within the outer foil, and loss of valuable information regarding particle size, whereas our experiments suggest that perforations through very thin foils (<10 microns) may still generate sub-circular holes with diameters closely related to the impacting particle diameter. It is also likely that the perforation diameter for a larger grain will prove to be independent of impact velocity above a threshold, which we believe to be substantially less than 5 kms^{-1}. There is thus good reason to use a thin (8 micron) top foil to act as proxy for particle dimension. However, if a thinner foil is employed, it requires protective coating, but aluminium must be avoided as it will seriously interfere with interpretation of residue.

Choice of a surface coating with the right attributes is very difficult, and only the metals rhodium and palladium seem suitable (figure 2). We have investigated the effect of increased surface density of a very thin metallic coating by generating a thin gold coat on the top foil used in our second impact experiment. We discovered that it did not prevent penetration by fine alumina grains (3 micron) and the high contrast in backscattered electron coefficient ($\delta\eta$)between the perforation ($\eta \sim 0$), the exposed surface of Kapton ($\eta \sim 0.06$) and the gold ($\eta \sim 0.4$) made the location of impact features an easy and rapid task in the SEM (figure 3). Although rhodium and palladium have a lower ETA value than gold, they do still yield a very distinctive bright background, and metal-coated particles from the top foil can be found easily on the uncoated foil beneath, revealing locations of forward-scattered target fragments, usually associated with projectile debris. Coating thus not only protects an upper foil, but also provides an easy way to find impact features.

5. Laboratory Impact Experiments

Our first experimental device utilised 6 thin foils separated from a sample of commercial MLI (as employed beneath a beta-cloth external shield). Each foil was aluminised on both sides and perforated (figure 4). The rear layer was a thick polyimide foil coated on one side with aluminium. The light gas gun (LGG) at the University of Kent (Burchell et al., 1999) was used to fire a mixed powder of 3 micron alumina (simulating solid rocket motor space debris) and 38-53 micron olivine grains (micrometeoroid), held in place within the sabot by a 1mm steel ball. The LGG shot velocity was 5.9 kms-1. A digital scanner was used to generate an image of light transmitted through holes in the normally opaque top foil, and showed large numbers of obvious perforations, falling into 4 populations

1) Pre-existing large vent holes in a regular pattern
2) A circular, cleanly defined 1mm diameter hole due to the steel ball
3) Abundant (dozens) of c. 60 micron circular holes, from the 38-53 micron irregularly shaped olivine component of buckshot, proven by analysis of associated residue on second foil
4) Very abundant (thousands) of c. 10 micron sub-circular holes, from the 3 micron alumina.

SEM and EDS of the second and third foil layers revealed abundant particle residue from olivine impacts (figure 5), although remnants of alumina could not be distinguished from the aluminised foil coating. The steel ball penetration through the fourth to sixth thin foil layers generated an irregular hole of increasing size, with extensive radial tearing and shrinkage. Traces of the steel could be found around the hole on all the thin foils (figure 6), providing an unexpected bonus of residue retention from a large, very energetic impact. The experiment thus demonstrated that particles of micron to millimetre scale and with kinetic energy values appropriate to those seen in LEO impacts do leave an indication of particle size and substantial quantities of diagnostic residue.

The second experiment utilised similar buckshot at a similar velocity, onto a similar configuration of foil thicknesses, but with no punched vent holes and with only the topmost 8 micron foil coated with metal, a thin sputtered gold coat on the top surface (fig. 7). Again, the three projectile types could be distinguished as three populations of holes in the top layer, and automated electron imagery and feature analysis confirmed the bimodality of the smaller hole sizes. Examination of the second foil, coated with carbon, revealed abundant olivine and alumina residues (figure 8), confirming that residue was emplaced and that its location could be matched to overlying holes and thus to particular penetration events. Damage due to the steel ball was seen to increase through the foils, to the extent of probable destruction of some areas that might otherwise have yielded residue from smaller particles. Iron derived from the steel could still be detected around the large holes.

6. Automation of impact and residue characterisation by analytical electron microscopy

The second device was also used as a test bed for automated sample imaging of penetrations and residue particle recognition in Jeol 5900LV and LEO 1455VP analytical variable pressure scanning electron microscopes, each fitted with an Oxford Instruments INCA energy dispersive X-ray microanalyser. Complete separated but otherwise unprepared foils were optically scanned (figure 7), then carefully attached to a conductive polymer holder (fig. 4). The ‘Automation’ routines in INCA were set up to drive the specimen stage from area to area across the entire width of the foil as exposed to impacts. In each area the programme acquires a backscattered electron image and an X-ray map to locate residues. A test run for 16 hours covered 10 areas, each of approximately 10^6 square microns, and located nearly one hundred residues in a single field of view (e.g. figure 8). A second automation routine involved production of a series of backscatter images, automated recognition of by residue by backscatter signal measurement above a zero value set for full thickness penetration (i.e. beam capture by the holder) and beneath the higher limit for the metallic coating. Following recognition of the impact feature location, the programme initiates a detailed scan and collection of an X-ray spectrum, from which compositional classification can be performed. For each particle, the stage co-ordinates are recorded, making later re-examination of the residue both simple and rapid. Measurements of the feature size and shape can be used in generation of graphical plots for specific residue types. This also allows precise matching of features between different foil layers, and together with the optical scans, this permits positive identification of impactor for each top foil penetration.

7. Future Work

7.1 Laboratory Experiments

To optimise the design for deployment in LEO, a third light gas gun experiment will be performed, primarily to capitalise upon the ability of thicker foils to prevent extensive tearing of the thinner foils by larger projectiles, whilst retaining their residue. The device configuration will have three thin rhodium/palladium-coated foils, followed by four thick foils, suspended in front of a 2mm thick solid PTFE rear plate. It is believed that this foil assembly will capture almost all the residue from the smallest particles on the top three foils, but will also provide suitable traps for the more energetic larger micrometeoroids such as were found to penetrate to 6 or 7 foils depth on SFU MLI (Graham et al., 2003). The thicker foils should provide sufficient strength to minimise failure around millimetre-scale penetrations, and to disrupt highest velocity particles into residue, whilst not compromising the ability of the top foil to record particle diameter.

7.2 Structure of the Flight Model Collector

The first flight model collector will probably have the structure shown in the vertical section of figure 9, and the perspective view of figure 10. The protective casing for the collector is an aluminium alloy box with the upper surface of the foils exposed through a square upper aperture of approximately 10 cm across (figure 11). The casing is perforated through each side to permit pressure equalisation, and is clamped to a 12 cm square planar base-plate for attachment to a spacecraft exterior. The entire assembly is designed to be stowed as a minor item on any mission bound for the ISS, to be deployed during extravehicular activity and returned when opportune.

8. Further applications of polymer foil collectors

The collector materials need not be restricted to containment within a small external casing. The foil components can be produced as metre-scale flexible sheets that could be rolled up for transport and unfurled for space-exposure and laboratory examination. The mass per square metre for the foil configuration in LGG experiment 3 would be less than 1 kg, and with minor modification could provide a substrate that collects from both sides and can be attached to a hollow metal frame, rotated into whichever direction is desired. If deployed in the ram direction, a single collector could therefore be used to monitor two different time intervals simply by turning the frame by 180 degrees.

9. Summary and Conclusions

Our laboratory experiments have shown that the structure of a proposed lightweight multilayer polymer foil collector (MULPEX) for deployment in low Earth orbit can successfully capture abundant residue from hypervelocity impact of a range of particle diameters from micrometre to millimetre scale. Automated, modern analytical SEM techniques can be used to find and characterise large numbers of residues on these types of polymer foil, both quickly and unambiguously. Together, the collector and automated analysis routines are suitable for opportunistic deployment.

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Illustrations

Figure 1. Photograph of 2nd test device after light gas gun shot, but before disassembly, seen from back. Small squares are 1mm across.

Figure 2. Comparison of the effect of EDS peak overlaps from the metallic surface coating upon the peaks from hypothetical residue compositions. The gold coating (right) causes severe interference with the detection of phosphorus and sulphur, whilst palladium coating has virtually no effect upon elements that are likely to be reliable indicators of projectile origin.

Figure 3. BE image of top foil from second test device, showing de-lamination of the metallic (gold) coating around the impact sites, making location very easy. Penetration through the underlying thin Kapton foil is visible as the dark central hole.

Figure 4. Third foil from the first test device, mounted on a conductive polymer holder and SEM stage projectiles. The oval outline marks the exposed area of 44mm long axis.

Figure 5. BEI of 2nd foil (no metallic coating) from 2nd test device, showing perforation and several small pits including an olivine residue grain (bright, arrowed).

Figure 6. Test Model 1 after light gas gun shot. Fourth foil. Optical scan image, BEI, aluminium and iron X-ray maps of large penetration through thin Kapton foil by stainless steel ball. Note evidence of Fe deposition on foil around hole.

Figure 7. Optical scan of entire gold-coated top foil from second test shot, showing large penetration by stainless steel ball and abundant minor perforations due to olivine and alumina grains. Pale area at bottom left is damage due to handling of fragile gold coating. Long axis is 44mm.

Figure 8. BEI of 2nd foil from 2nd test device reveals abundant small perforations and numerous residues. Tips of small NE-pointing arrows show locations of abundant olivine residue particles, larger SE-pointing arrows show location of alumina residues.

Figure 9. ED X-ray spectra obtained by extraction of raw data from high resolution X-ray maps showing individual residue particles in an area such as figure 5. These spectra are of sufficient quality for recognition of a particle worthy of further investigation and classification as space debris or micrometeoroid in origin.

Figure 10. Vertical cross section through a MULPEX container, enclosing a ten foil version of the foil collector, four thin upper foils overlying six thicker foils and all supported on PTFE ‘window-frames’.

Figure 11. Schematic perspective sketch of a MULPEX collector with casing removed. Note vent holes around sides to permit pressure equalisation between sheets of foil.

Figure 12. Schematic perspective sketch of a MULPEX collector with casing in place.

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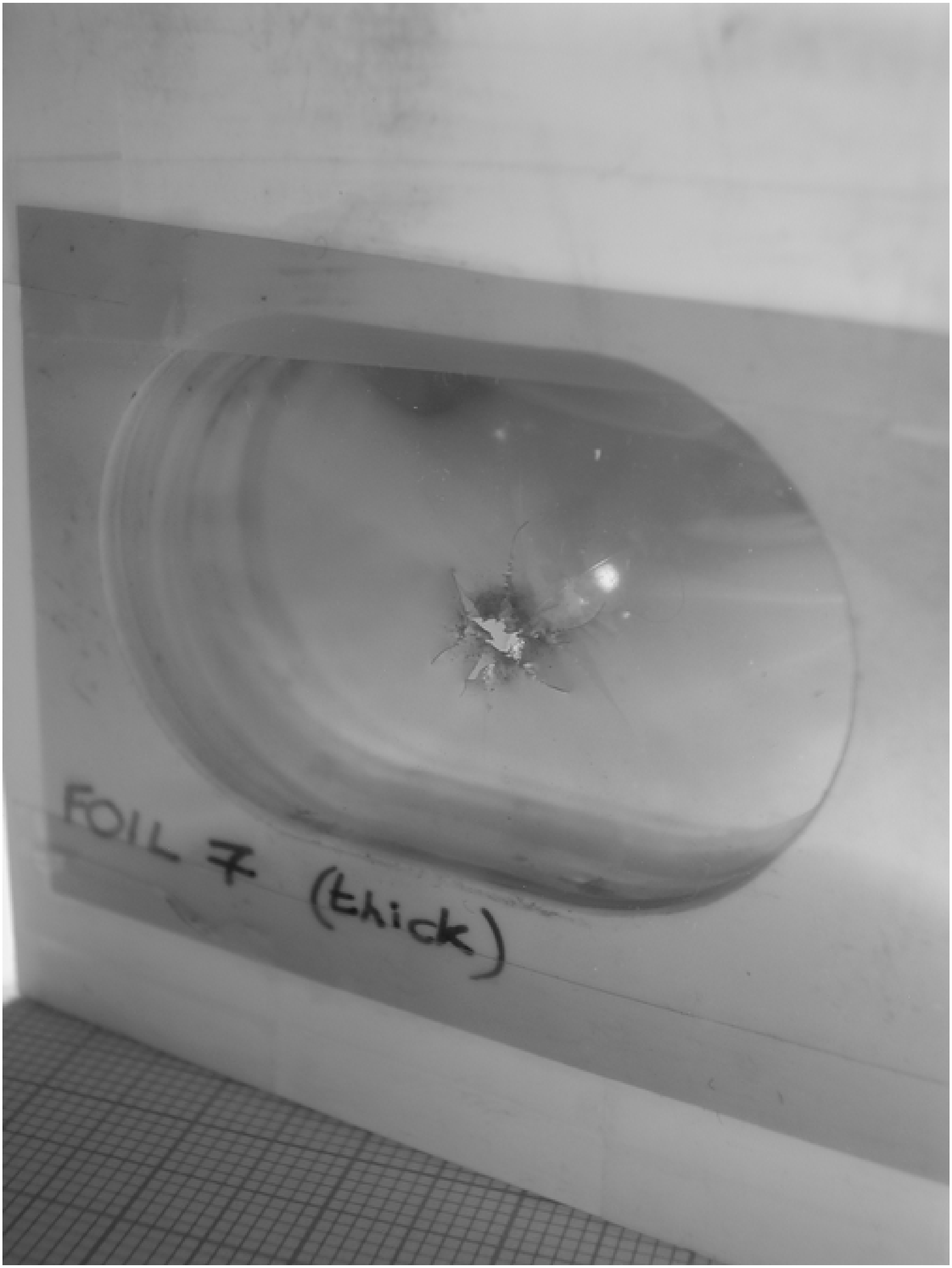

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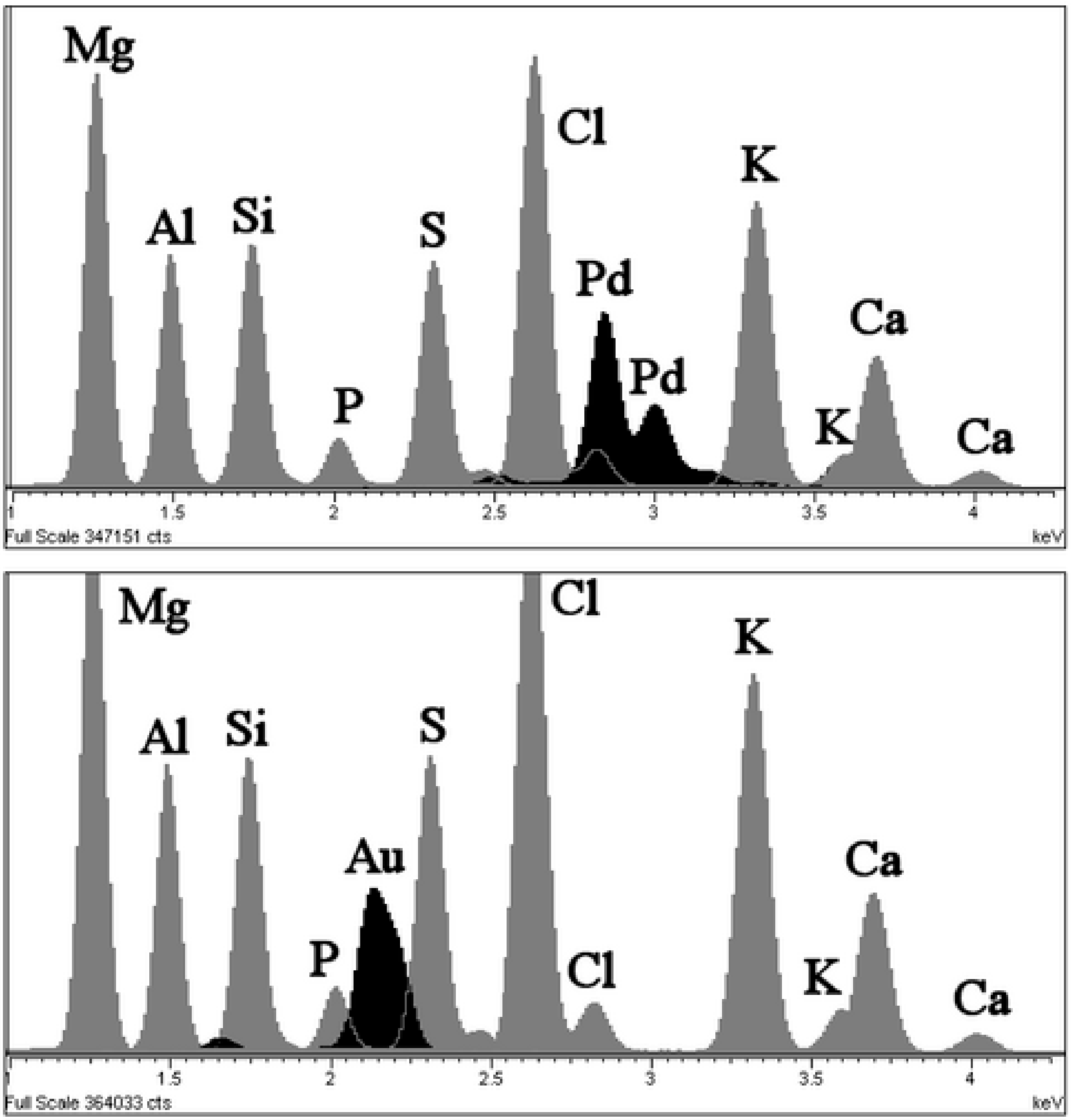

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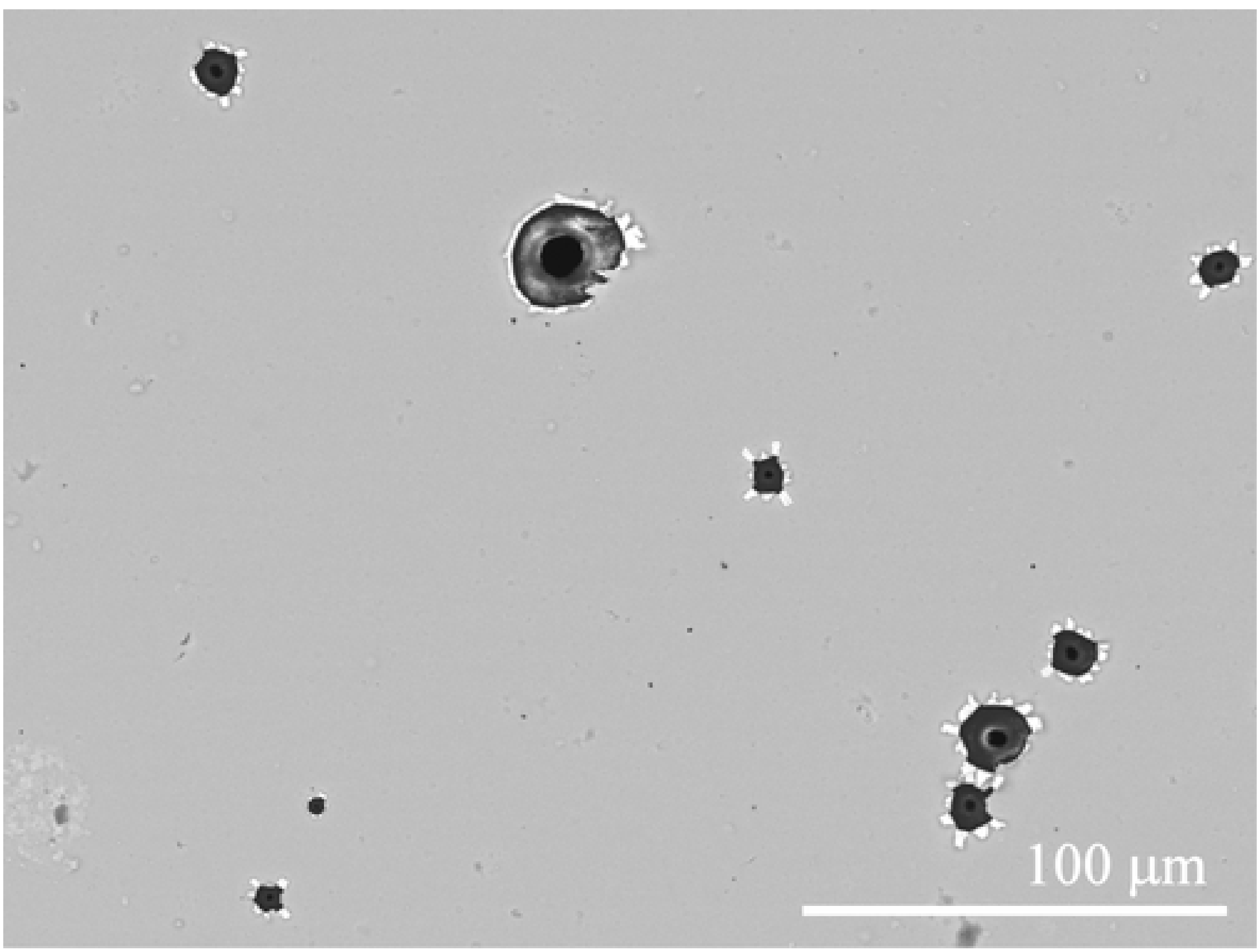

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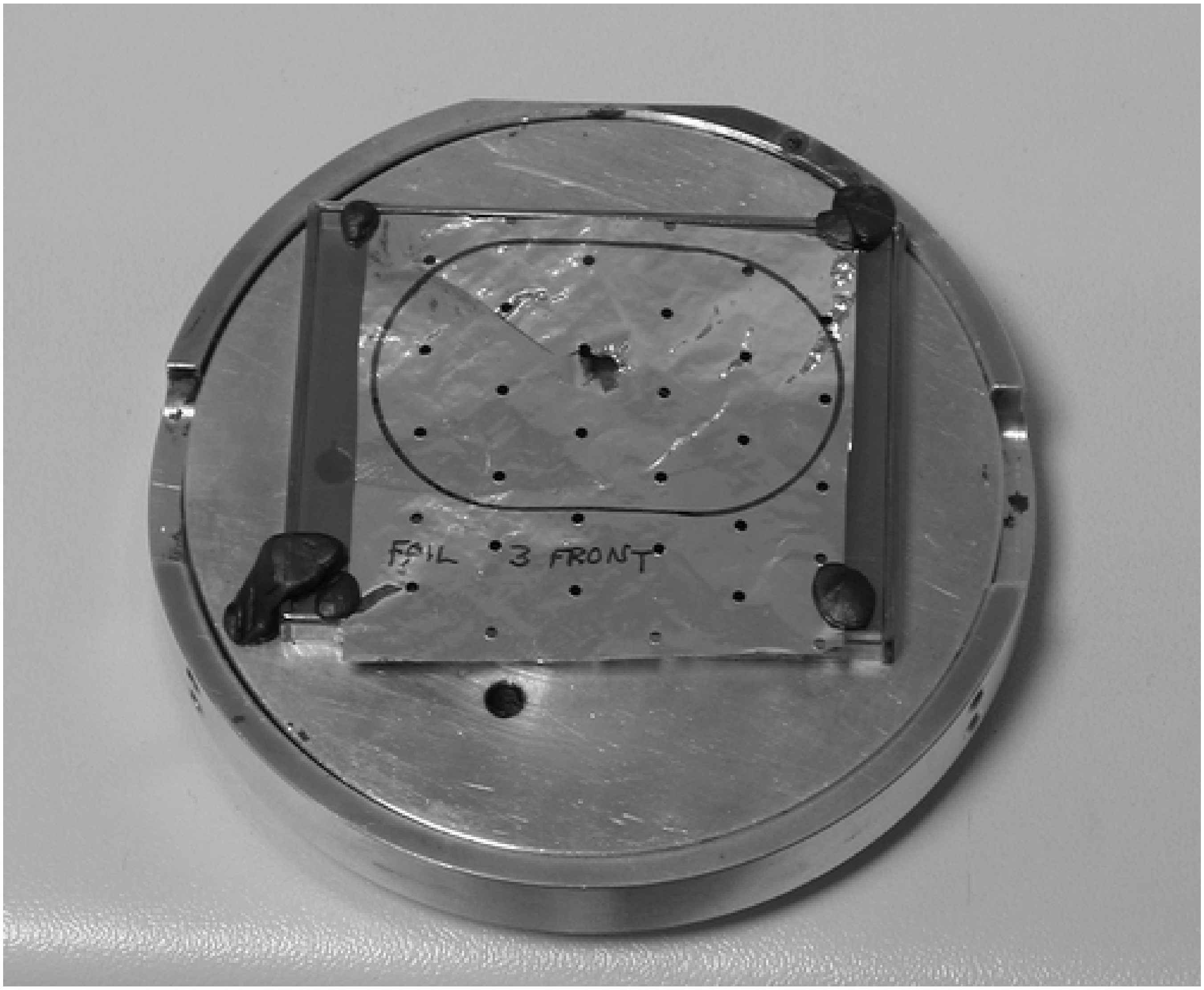

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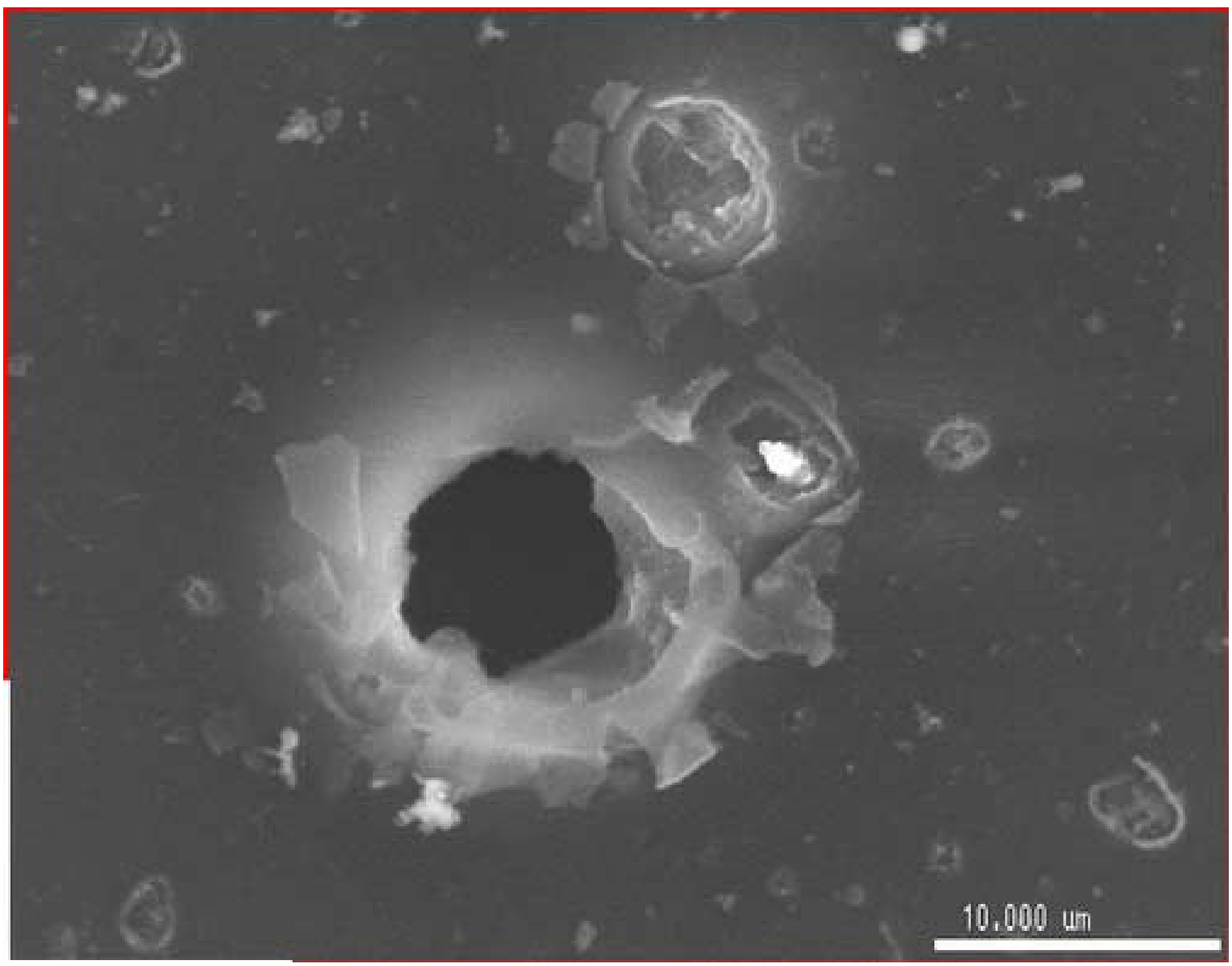

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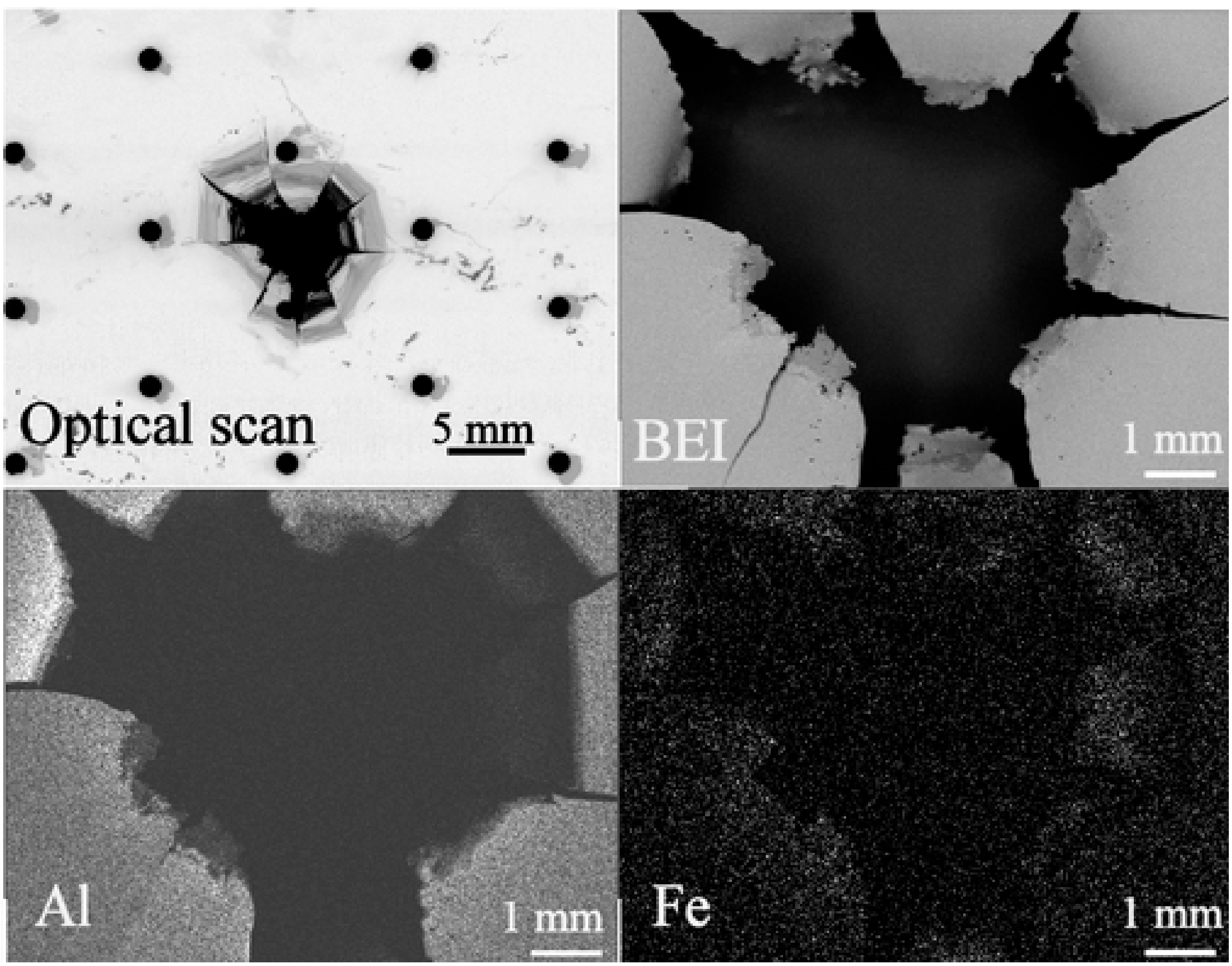

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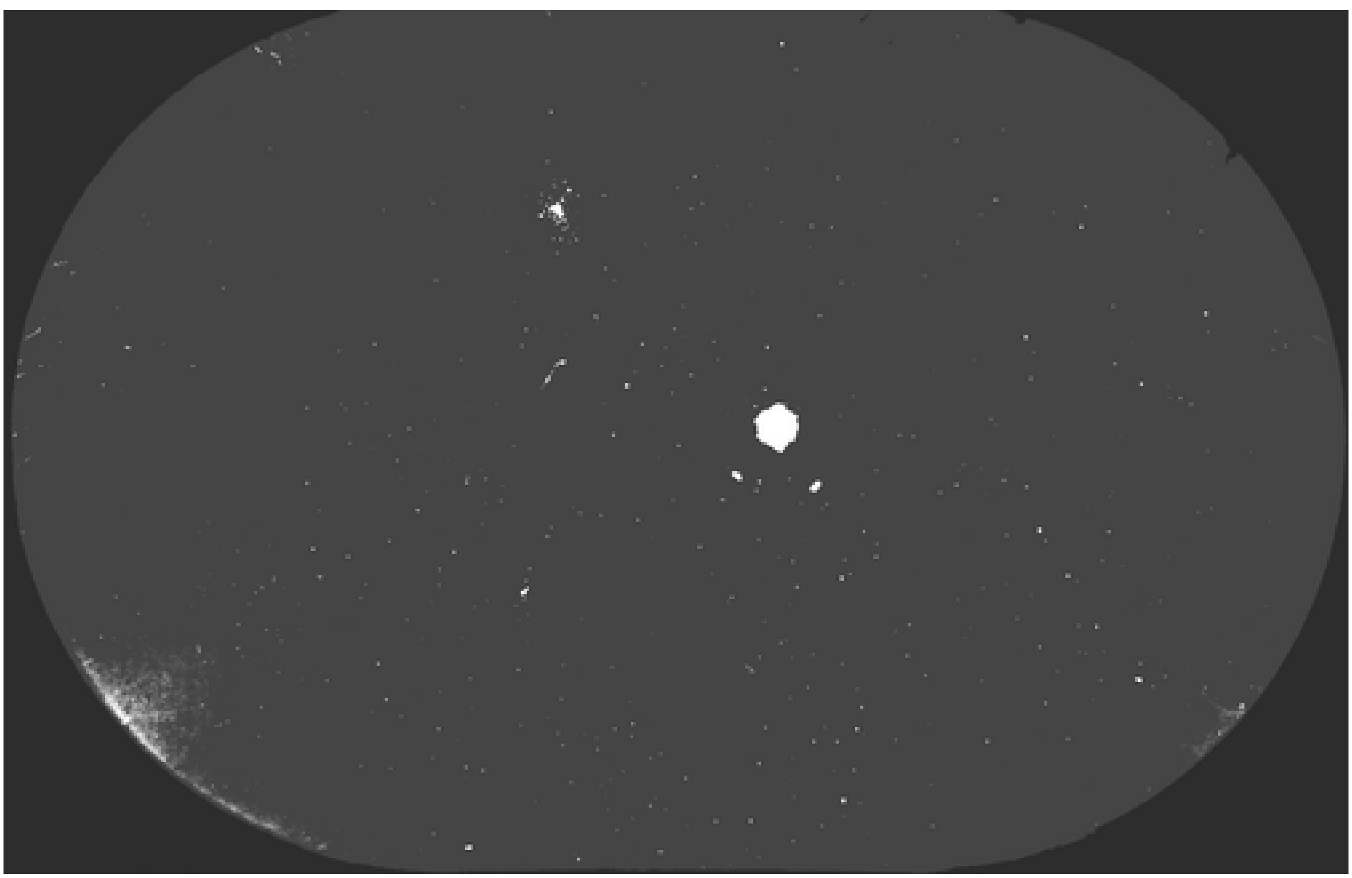

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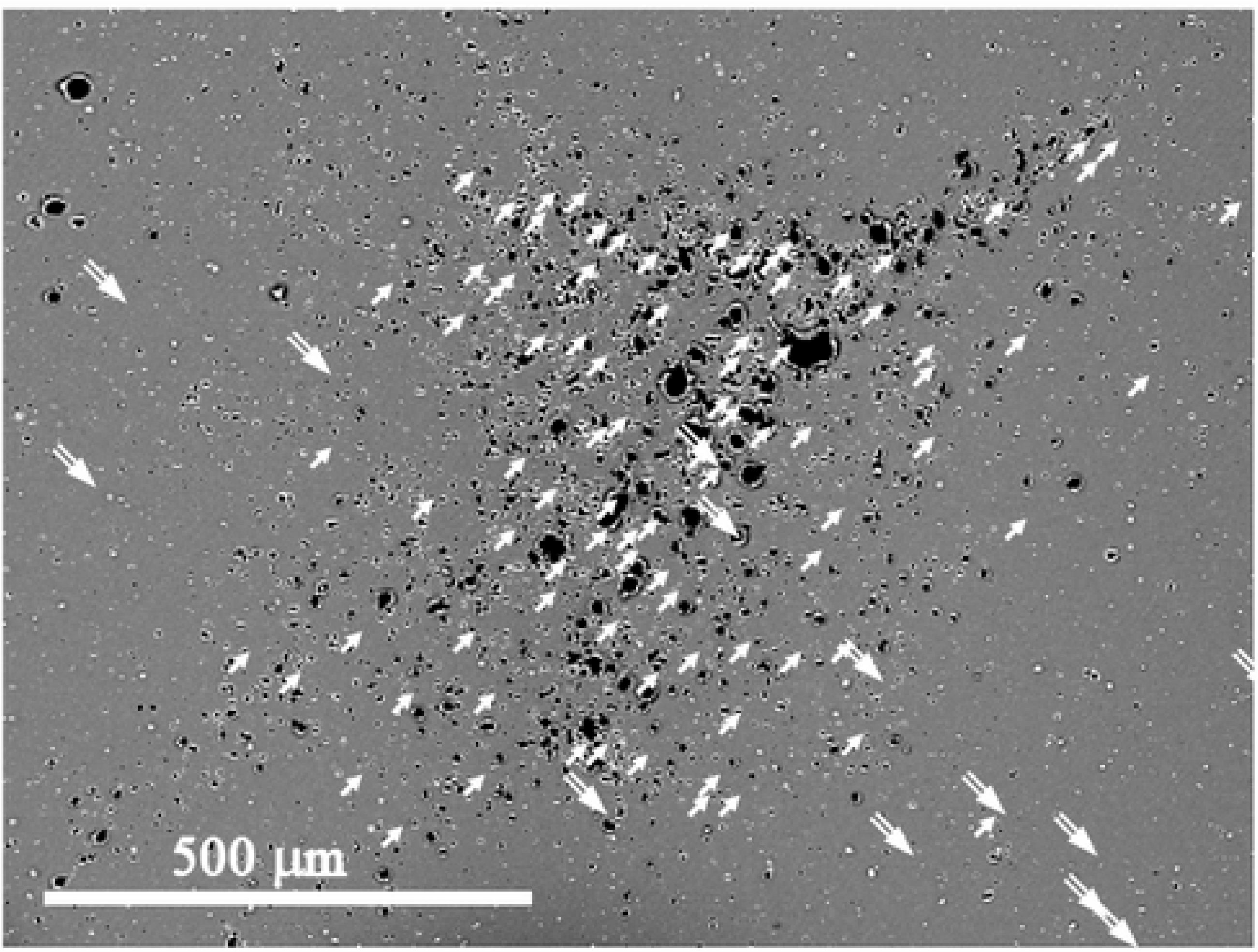

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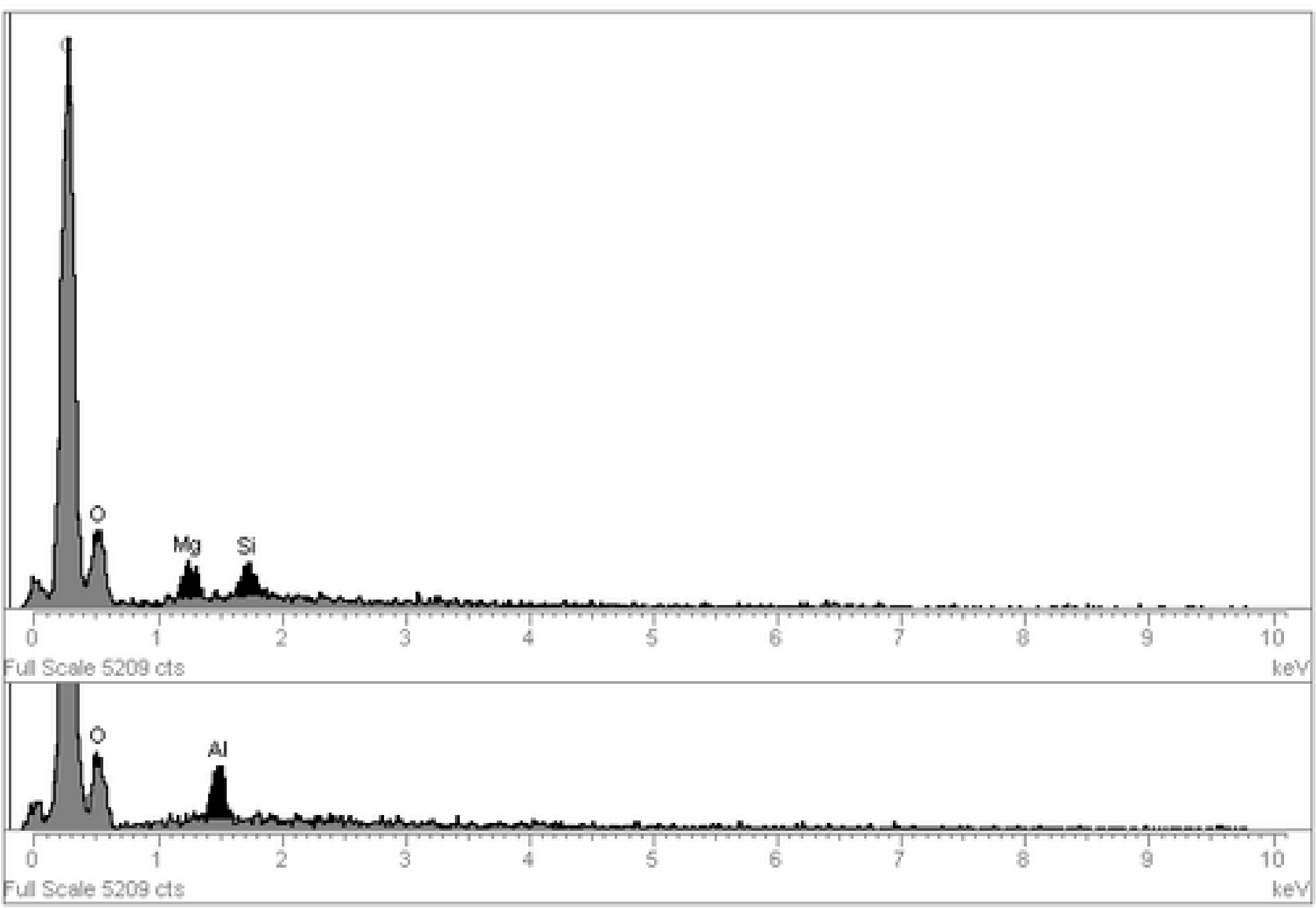

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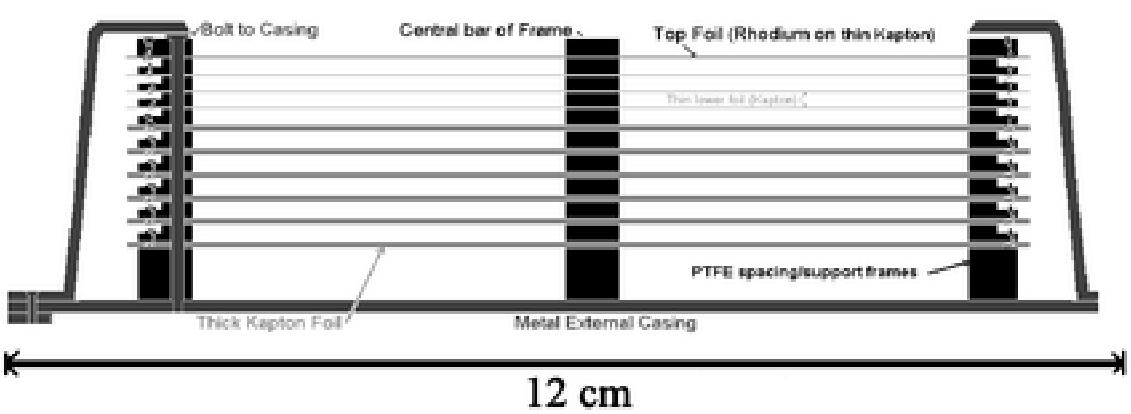

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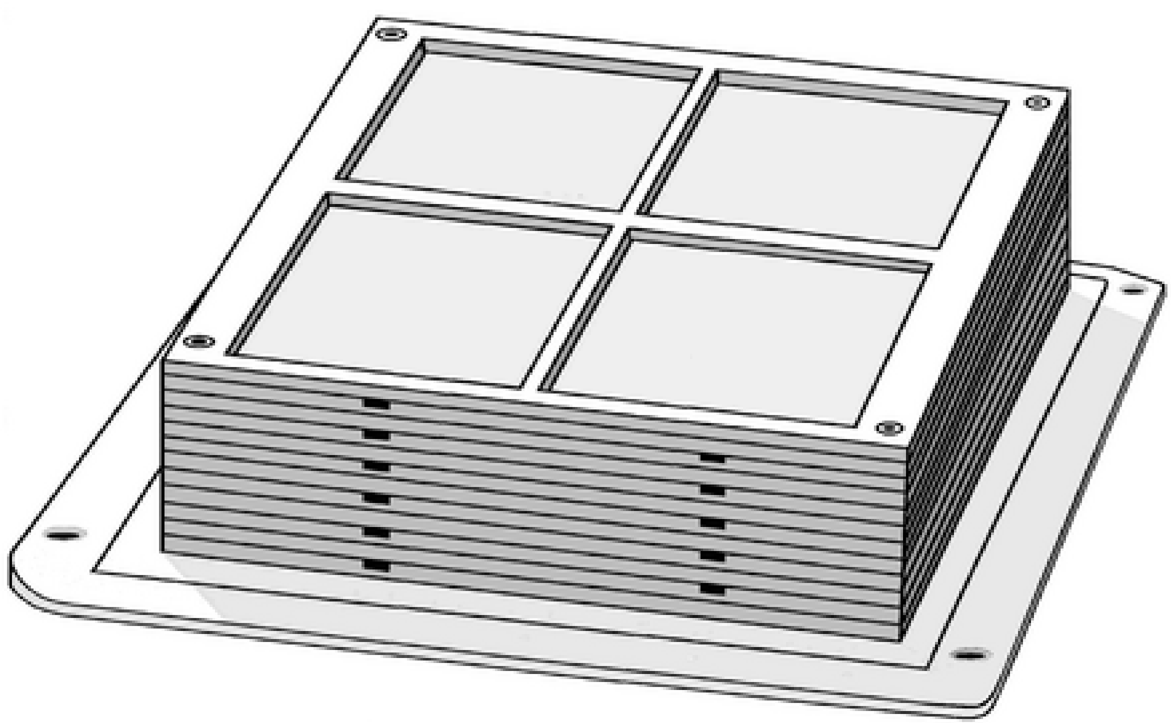

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